

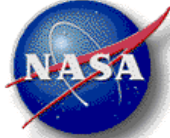


Status on the Development of CERMET Fuels For A Nuclear Cryogenic Propulsion Stage (NCPS)

NASA Advanced Exploration Systems (AES) Program

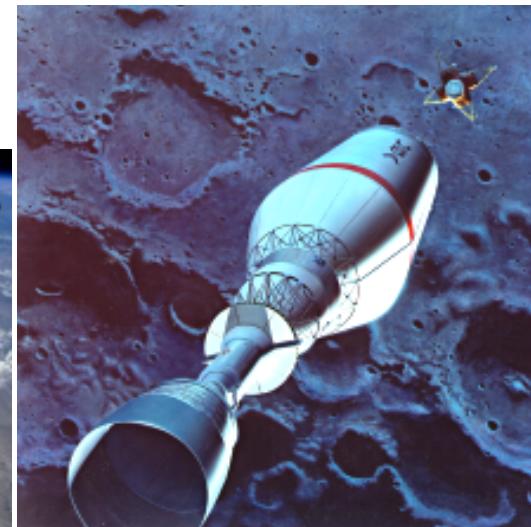
**49th AIAA Joint Propulsion
Conference
San Jose, CA
July 15-17, 2013**

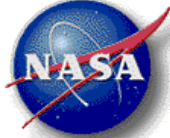
***J. Broadway, R. Hickman, O. Mireles
NASA Marshall Space Flight Center
jeramie.w.broadway@nasa.gov***



Presentation Outline

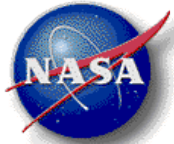
- AES Nuclear Cryogenic Propulsion Stage (NCPS) Project
- NCPS Task4 fuel design and fabrication
- CERMET material development
- UO₂ particle development
- CVD coated particle development
- Hot Isostatic Press (HIP) fabrication process & fabrication
- Fuel element testing
- Conclusions





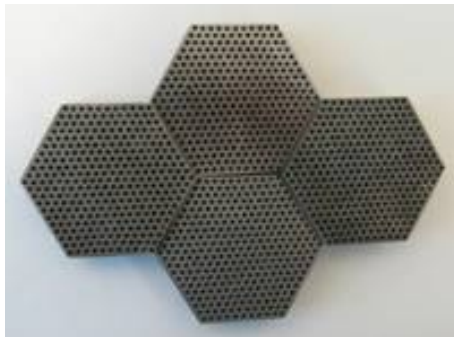
Nuclear Cryogenic Propulsion Stage (NCPS)

- NTP is a game changing technology
 - Increased Isp compared to chemical propulsion (900 sec)
 - Multiple restart capability
 - Increased T/W and reduced trip times
- NCPS established as an Advanced Exploration Systems (AES) Program
- The three year effort began in FY12 and is reviewed annually
- NCPS Tasks
 - Pre-conceptual design and system architecture integration
 - **Fuel design, fabrication and testing**
 - Nuclear Thermal Rocket Element Environmental Simulator (NTREES)
 - Affordable Development and Qualification Strategy
- Critical need for fuel development
 - Lack of qualified fuel material
 - Long lead activity
- Fuels objective is to demonstrate the capability to fabricate and test full scale elements

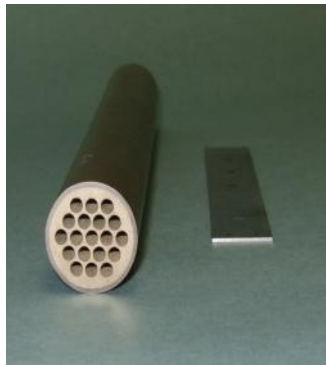


NCPS Task 4- Fuel Design / Fabrication

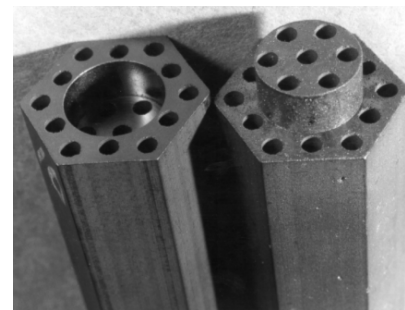
- Goals
 - Mature CERMET and Graphite based fuel materials
 - Develop and demonstrate critical technologies and capabilities
- Objective
 - Along with other NASA centers and DOE, optimize manufacturing processes to develop an NTP fuel material
 - Idaho National Laboratory (INL)
 - Oak Ridge National Laboratory (ORNL)
 - Fabricate CERMET and graphite composite fuel element samples with depleted uranium fuel particles
 - Complete mechanical and thermal property testing to develop an understanding of the process/property/structure relationship
 - Perform full scale element testing of CERMET and graphite fuels



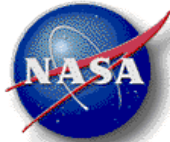
331 Channel Hex Demo (MSFC)



19 Channel HIP Demo (MSFC)

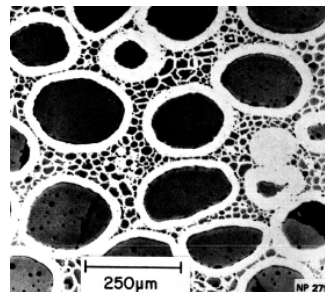
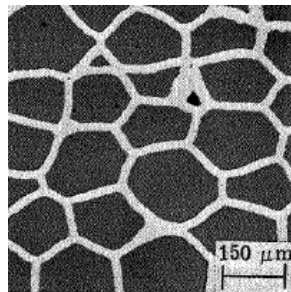


Graphite Composite Fuel Element
(Rover/NERVA)

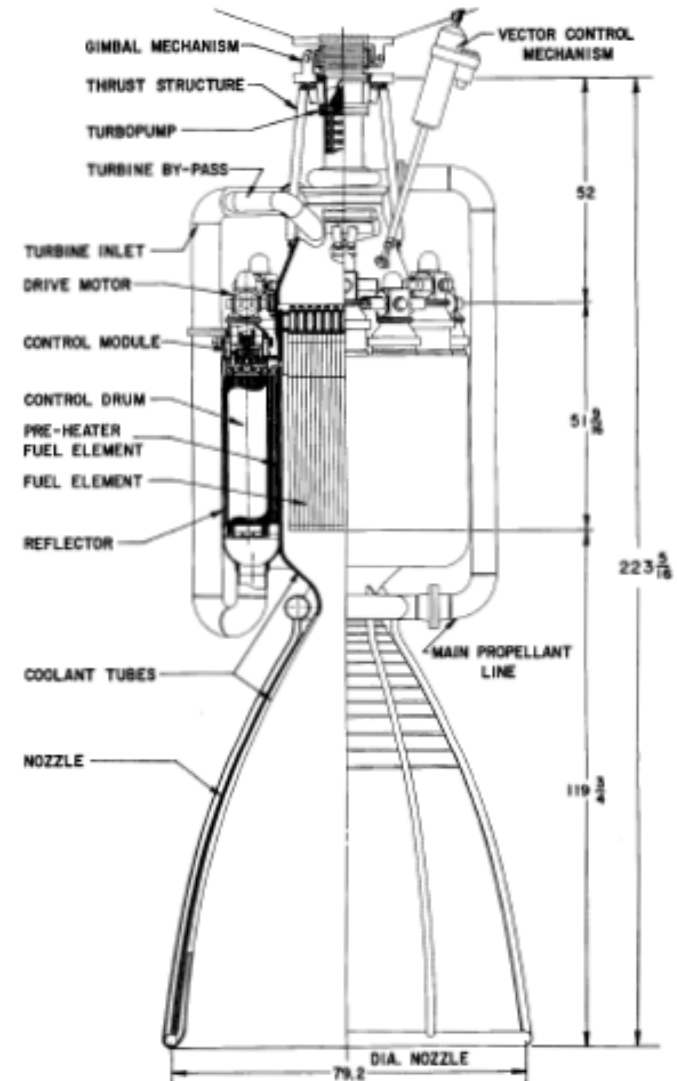


What is a CERMET Fuel?

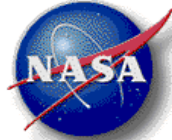
- CERMET fuels consist of a metal matrix with embedded ceramic fuel particles
 - W matrix (high melting point, H₂ compatibility)
 - UO₂, UN, (U,Zr)CN fuel particles
- Developed in 1960's as an alternate to graphite based fuels
 - Long operating life (>10 hrs, 2800k)
 - Multiple restart capability at high specific impulse (800-900 sec)
- Improved fission product retention
- Metal phase improves toughness



W - light phase, UO₂ - dark phase

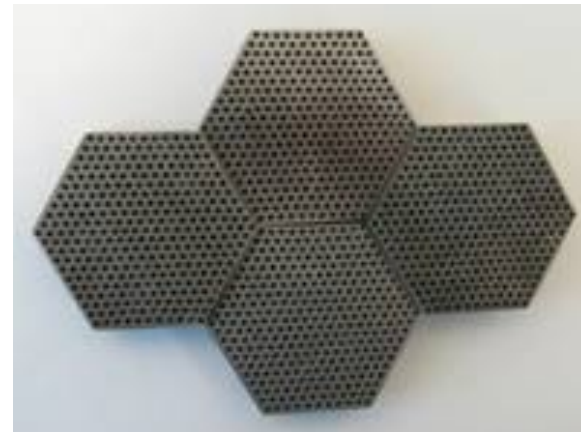


ANL 2000MW CERMET Engine

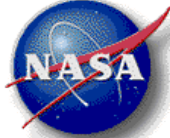


CERMET Fuel Material Development

- MSFC CERMET development based on previous programs (ANL & GE710)
 - Develop feedstocks for HIP processing; optimizing UO₂ particle size, shape and density
 - Develop and understand HIP parameter influence on consolidated part
 - Part shrinkage during HIP to achieve dimensional tolerance
 - Size and shape of particles post HIP
 - Density
 - Mixed particle material performance versus W coated particles
 - Develop W surface cladding
 - Complete surface cladding on OML of elements
 - Complete claddings on IML of coolant channels
 - Additional stabilizers to increase life
 - Screening of fuel materials in hydrogen environment
 - Coupon level testing to quickly screen materials
 - Full scale testing with prototypic environments and mission cycles
- Iterative approach
 - Fabricate, test and optimize

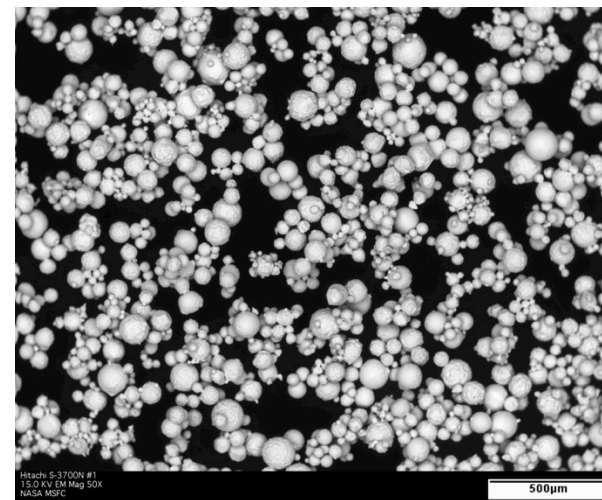


331 Channel ANL 2000MW Demonstration Elements



dUO2 Particle Development

- Development focused on particle size, shape, density and morphology
 - Mixed particle HIPing focused on obtaining an order of magnitude difference between W and dUO2 particles to achieve increase packing density
 - +5/-15 μm W
 - +90/-106 μm dUO2
 - Coated particle HIPing will require fine particle spherical dUO2
 - Currently low availability of fine particle spherical dUO2
- CSNR internal gelation process development
 - Working on procurement of 3kg of dUO2
 - 100 +/-25 μm spherical particles
- ORNL Sol-Gel process development
 - Multiple iteration study to develop fine particle dUO2

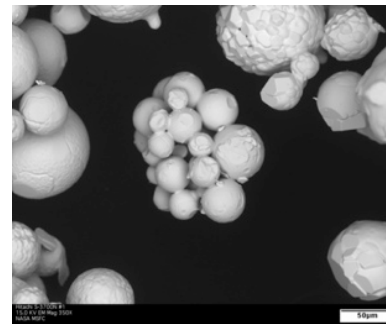


SEM Image 50x ORNL SG DU

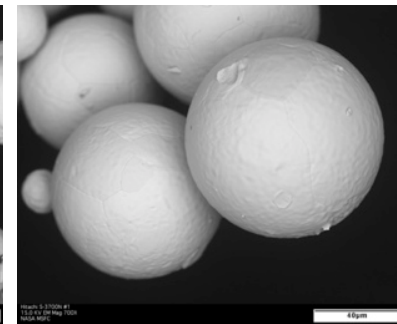


ORNL Sol-Gel Development

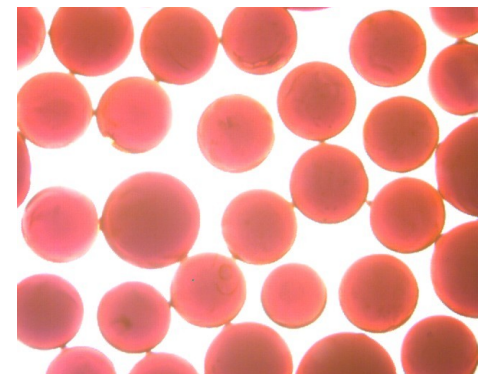
- Currently have a qualified process for 300 μ m TRISO fuel particles
- Completed a study to deliver fine spherical particles
 - No system modifications; varied system parameters
 - Understand smallest particles achievable
 - Understand yields and distributions
- Delivered ~140g of spherical dUO₂ particles
 - ~50g, <75 μ m
 - ~90g, +75/-150 μ m
 - ~2g, +150/-212 μ m
- Results
 - Good spherocity and density
 - Able to produce finer particles but high distribution
 - Agglomeration of fine particles to larger during sintering
 - Only contamination found was from Al₂O₃ boat used during sintering
- Second phase to produce 3kg of 100+/-25 μ m particles
 - Switch to a smaller needle during processing
 - Obtain tighter distribution of particles, 100 +/-25 μ m
 - 3kg complete through sol-gel and are currently completing sintering
 - The smaller needles and modified parameters are producing a tighter distribution



SEM Image 350x ORNL SG dU



SEM Image 700x ORNL SG dU

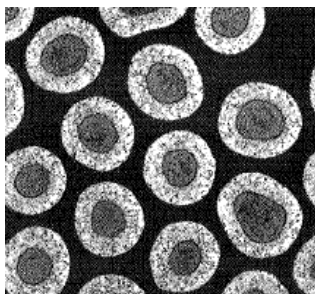
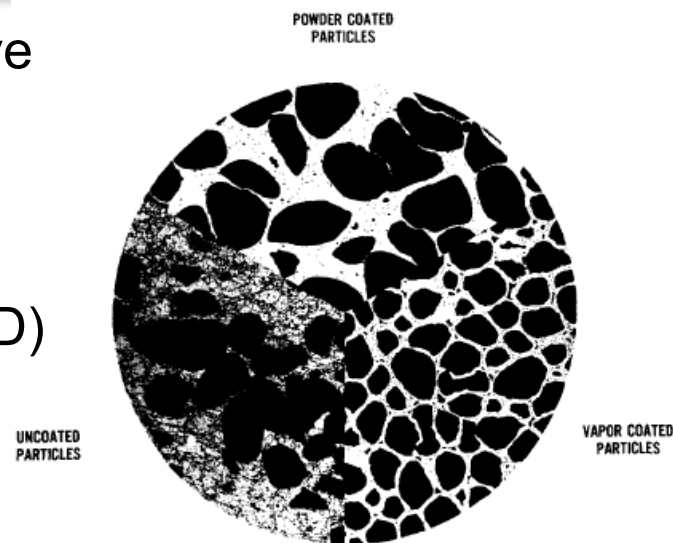


ORNL phase II particles. Pre-sintering

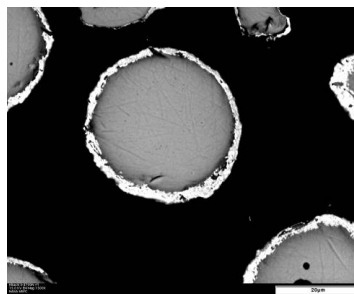


CVD Tungsten Coated UO₂

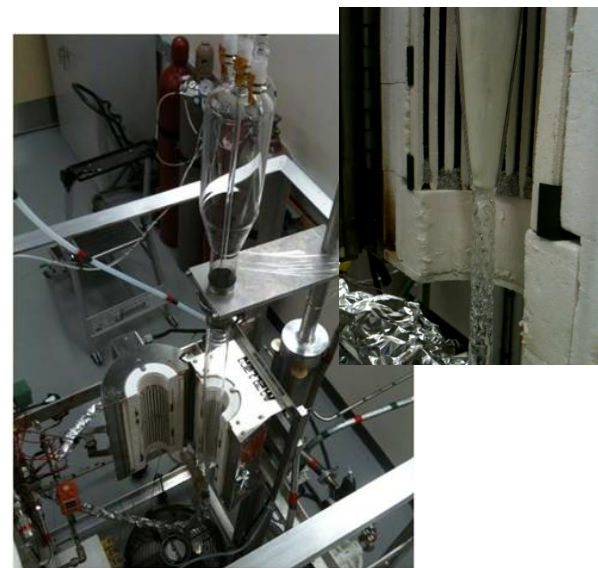
- W coated UO₂ particles are required to improve properties and minimize fuel loss
 - Clearly demonstrated on previous programs
 - Prevents particle contact and agglomeration
- Fluidized bed Chemical Vapor Deposition (CVD)
 - H₂ reduction of WCl₆
- Multiple system design iterations
 - Reactor, expander, sublimator, and feed system
- Demonstrated W coating on ZrO₂
- Currently optimizing reactor and sublimator
 - Requires sublimation of granular WCl₆



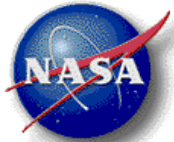
W coated UO₂
(GRC, 1965)



W coated ZrO₂
(MSFC)

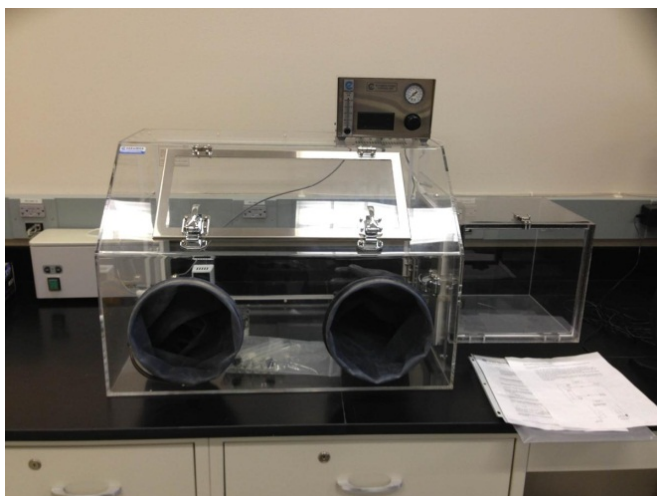


MSFC Fluidized Bed CVD System

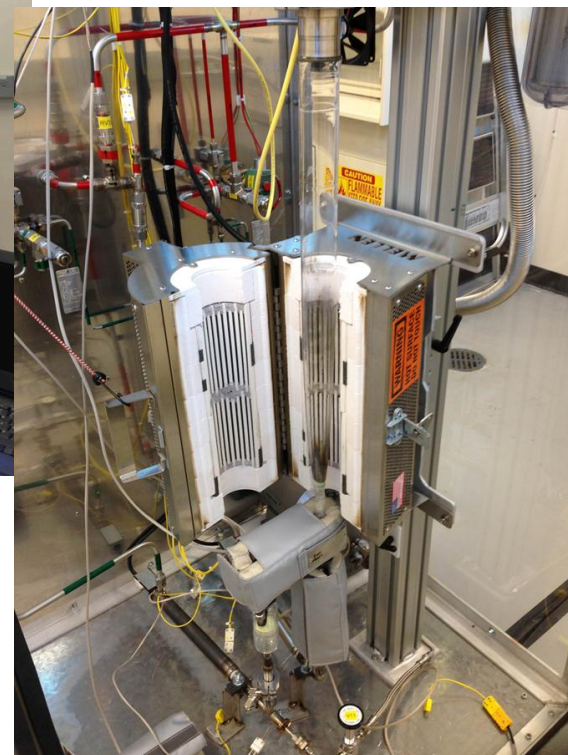
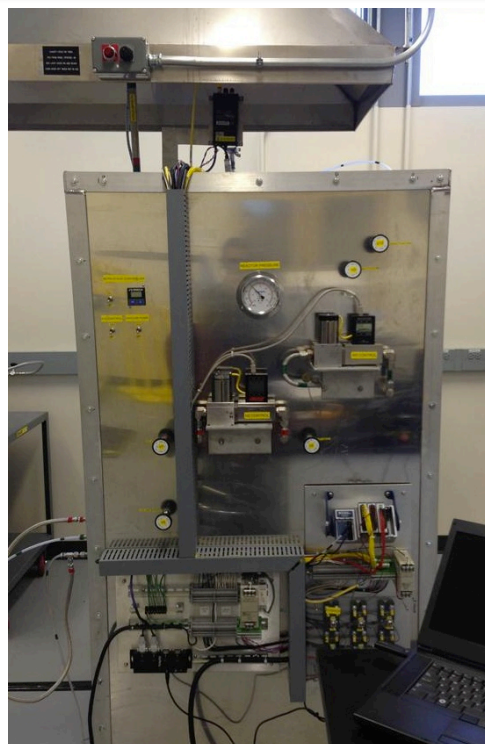


CVD System Status

- Installed in new lab
 - CVD upgrade complete
 - System check outs underway
 - System performance test
 - Coating trials
 - Optimizing process variables
 - DAQ system operational
- WCl_6 glove box functional



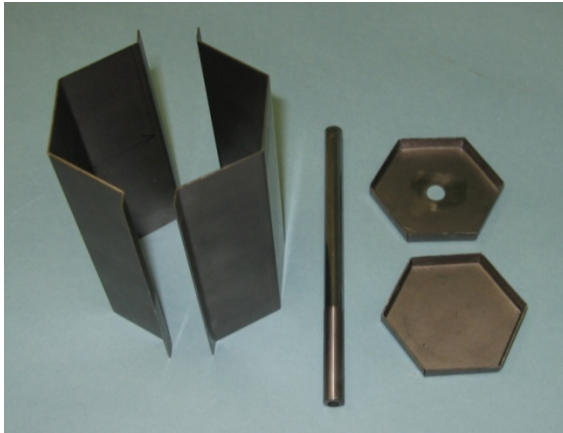
WCl_6 handling glove box



CVD System



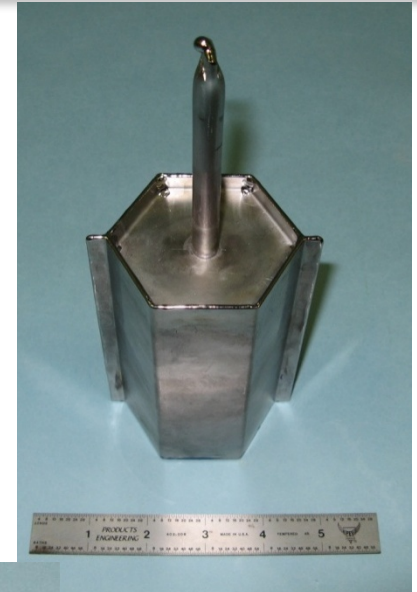
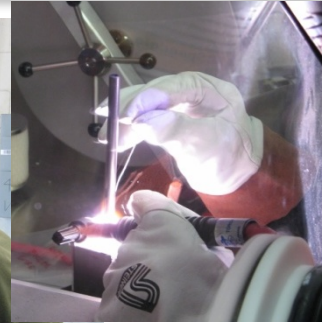
Net Shape HIP Fabrication Process



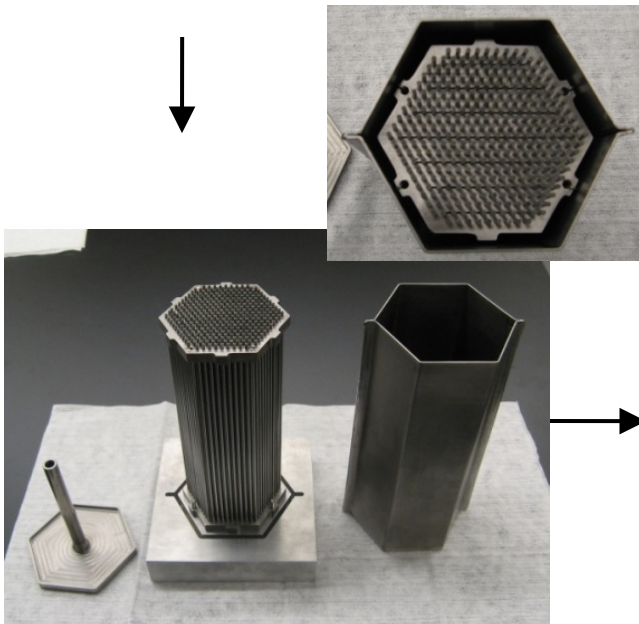
Hexagonal HIP can components



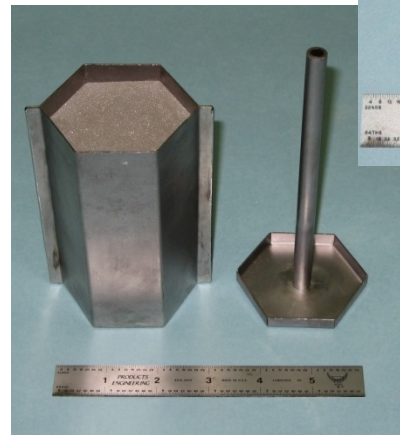
Final closeout weld



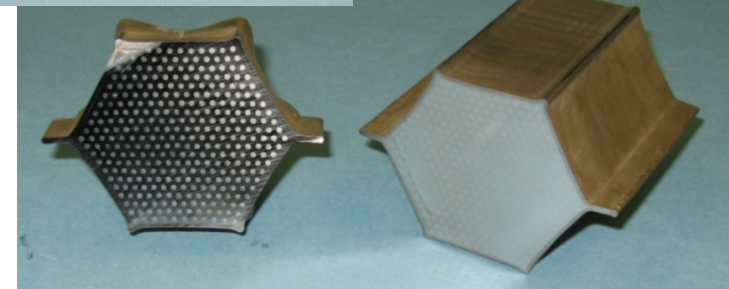
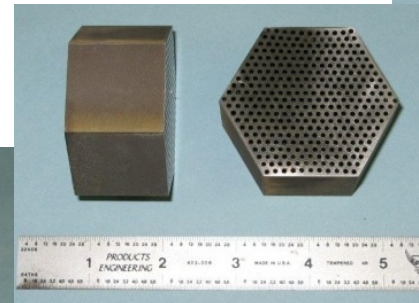
Sealed HIP Can



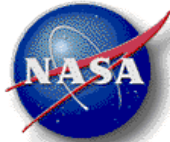
Mo Mandrel assembly



HIP can after powder fill

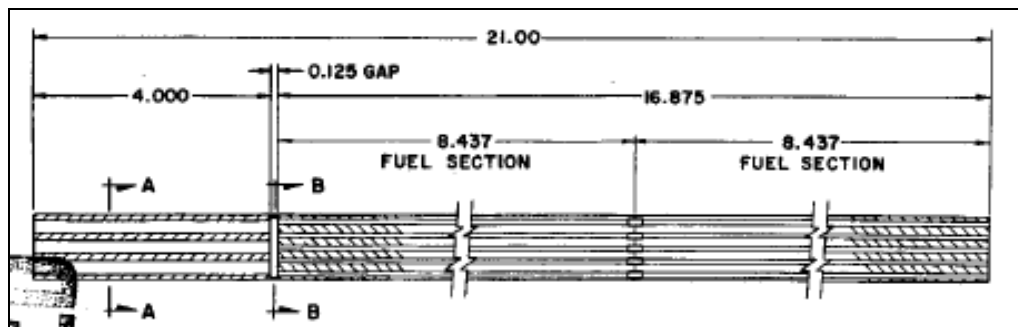


Can assembly after HIP cycle

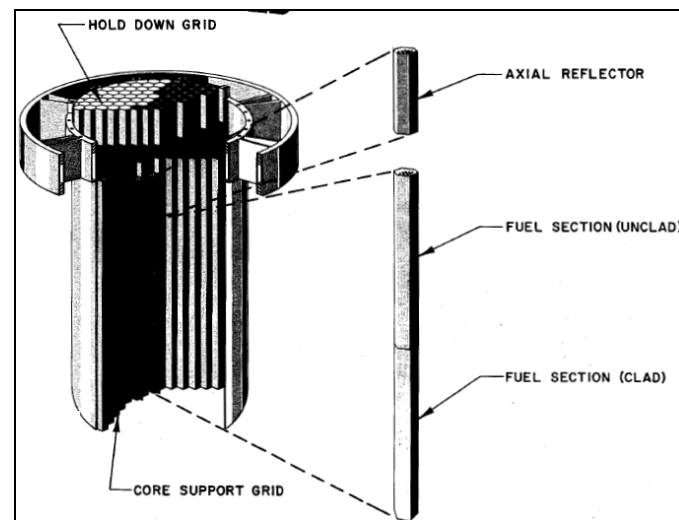


NCPS CERMET Reference Design

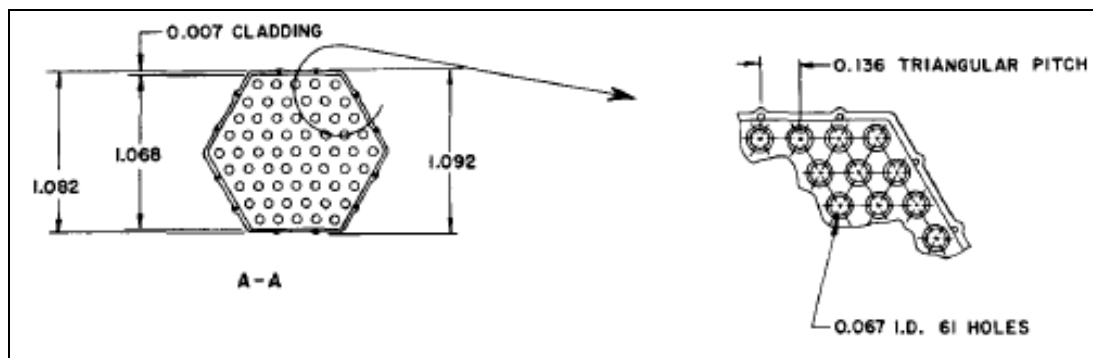
- ANL 200MW fuel element
 - 16.9" fueled length
 - 61 coolant channels @ $\varnothing 0.067$ "
 - 1.09" f-t-f
 - 60 vol% UO₂ fuel loading



Fuel Element and Axial Reflector



Reactor Core Assembly



Fuel Element Cladded Section

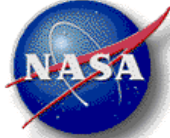


MSFC HIP System Upgrade

- MSFC has a large HIP system but required refurbishing
- HIP system upgrade completed in November 2012
 - Complete upgrade of control systems
 - Refurbishment of high pressure valve rack
 - Refurbishment of high pressure tank farm
- Allows MSFC to have a completely in-house fuel fabrication process
- System Specifications
 - Pressure vessel hot zone dimensions: Ø8" x 30"L
 - Graphite furnace capable of 2000°C
 - Pressure rated to 35000psi
- Included in MSFC NRC license to process DU
- System is operational with W-UO₂ HIP parameter development beginning soon

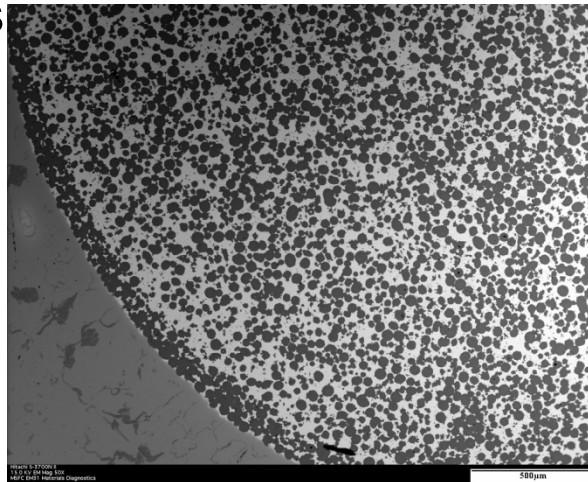


MSFC HIP pressure vessel (right). Graphite furnace removed (left).

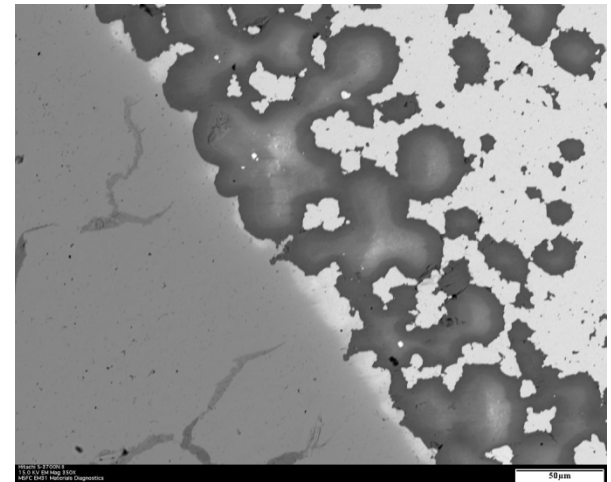


W-ZrO₂ HIP Initial HIP Cycle

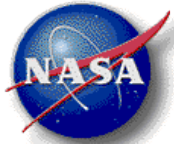
- Completed and initial HIP cycle for operational checkout of the new system
- Cycled at 1800°C, 35ksi with 2 hour hold with minimal operational issues
- Ø0.375" HIP can ID, 2.0" sample length
- W-60vol% ZrO₂
 - +5/-15µm W particles
 - +45/-53µm spherical ZrO₂ particles
- Not an optimum mixed particle blend based on HIP powder metallurgy practices



SEM Image 50x

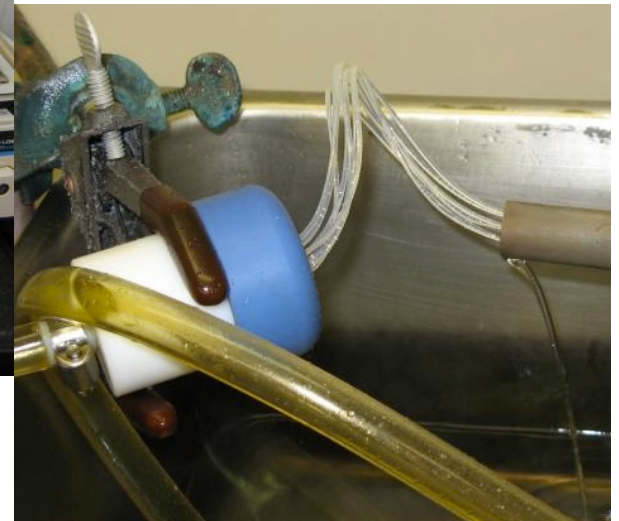
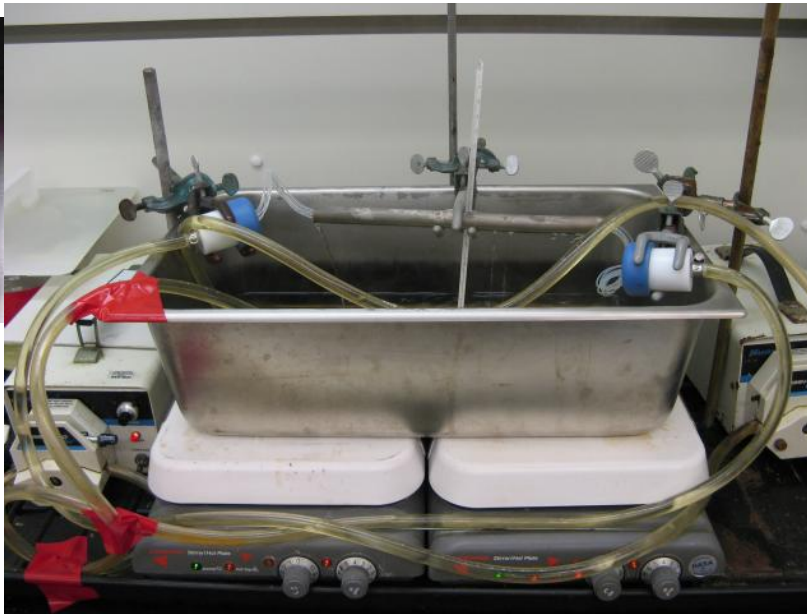
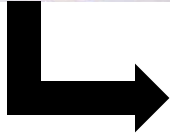


SEM Image 350x



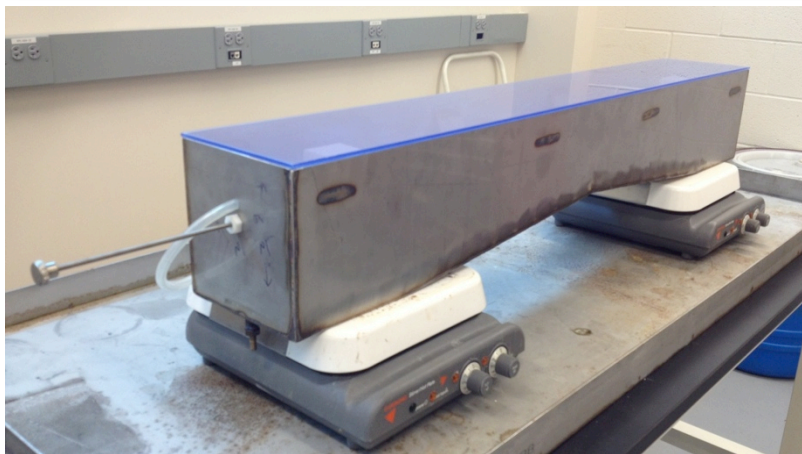
HIPed Fuel Element Etch System Design

- Mandrel removal post HIP is a critical part of fabricating an element
- Machining is not an option based on the small diameters and large lengths of the elements
- Chemical etch is a proven process but still difficult for the fuel element geometries

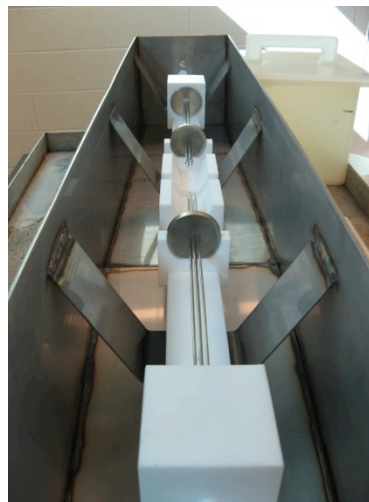




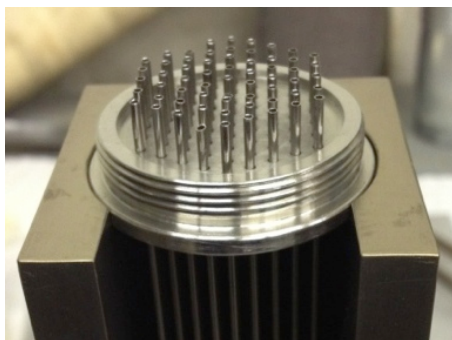
Optimized Chemical Etching System



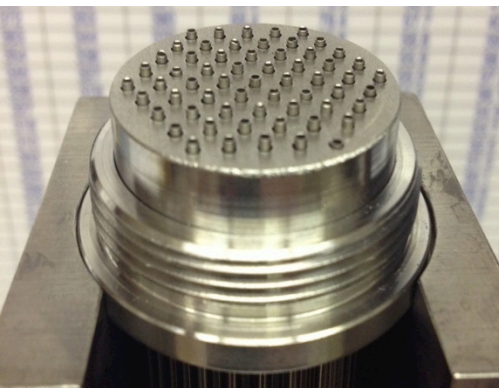
Front view of the chemical etching system. The system is designed to etch 7-channel and 61-channel fuel elements which will be tested in the Compact Fuel Element Environmental Tester (CFEET), and in the Nuclear Thermal Rocket Environmental Element Simulator (NTREES).



Top view of the chemical etching system configured to etch a 7-channel fuel element. The 7-channel fuel elements will be tested in the Compact Fuel Element Environmental Tester (CFEET).



Top view of a 61-channel etch component just prior to the brazing process, showing the channel head and etch tubes positioned in the brazing assembly.



Left: 61 channel head post braze. Three tubes did not braise during the cycle. Numerous tubes bent during the cycle as well. Above: 61 channel head with modified tooling to prevent bending in the tubes. Will use braze foil instead of braze paste.



Complete front view of a 61-channel etch component just prior to the brazing process. This component will be used to chemically etch the coolant channels in a uranium dioxide- tungsten fuel element.

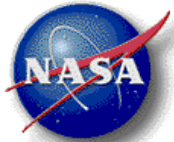


Fuel Element Testing

- Hot Hydrogen Testing
 - Sample will be tested in a flowing H₂ environment to evaluate material performance
 - Evaluate fuel mass loss, microstructure, claddings, particle coatings and stabilizers
- CFEET Test System
 - 2800-3000K temperatures with RF heating and low flow H₂
 - Small scale sample testing, 0.5" - 1" diameter x 1" – 3" long
 - Rapid testing to evaluate materials before committing resources to full scale samples
- NTREES Test System
 - 2800-3000K temperatures with RF heating
 - Prototypical reactor pressures and flowing H₂
 - Large scale element testing, prototypic element dimensions, 1.09" ftf x 16.8" long, 61 cha

Sample Description (W-60 volume % UO ₂)	Specimen Geometry	Peak Temperature	Thermal Cycles	Environment
Uncoated UO ₂	CFEET Slug	2850K	10	Flowing H ₂
Uncoated UO ₂	CFEET 7-Hole ANL 200MW	2850K	10	Flowing H ₂
Uncoated w/clad	CFEET 7-Hole ANL 200MW	2850K	10	Flowing H ₂
Coated UO ₂	CFEET Slug	2850K	10	Flowing H ₂
Coated UO ₂	CFEET 7-Hole ANL 200MW	2850K	10	Flowing H ₂
Coated UO ₂ w/clad	CFEET 7-Hole ANL 200MW	2850K	10	Flowing H ₂
*Coated UO ₂ w/clad	Subscale NTREES ANL 200MW	2850K	10	Flowing H ₂
Stabilized coated UO ₂ w/clad	CFEET 7-Hole ANL 200MW	2850K	10	Flowing H ₂
Optimized M&P #1	CFEET 7-Hole ANL 200MW	2850K	10	Flowing H ₂
*Optimized M&P #1	Subscale NTREES ANL 200MW	2850K	10	Flowing H ₂
Optimized M&P #2	CFEET 7-Hole ANL 200MW	2850K	10	Flowing H ₂
*Optimized M&P #2	NTREES ANL 200MW Element	2850K	10	Flowing H ₂

*NCPS fuel design and fabrication task milestone



Compact Fuel Element Environment Test (CFEET)

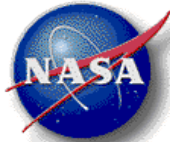
- CFEET upgrade to 50kW power supply
- Redesigned chamber and containment for dU
 - Bottom loading of sample
 - HEPA filtered exhaust
 - DAQ system upgrade
- Redesigned and optimized coil design
- Ops checks are complete on the following subsystems:
 - Burnstack T/C and solenoid valve controller
 - Mass flow controller
 - Vacuum pump isolation valves and interlocks
 - Vacuum Pump
- First test run complete
 - Pure tungsten slug sample
 - Achieved 2600K @ 30% pwr levels
 - Argon environment



CFEET pumps and containment

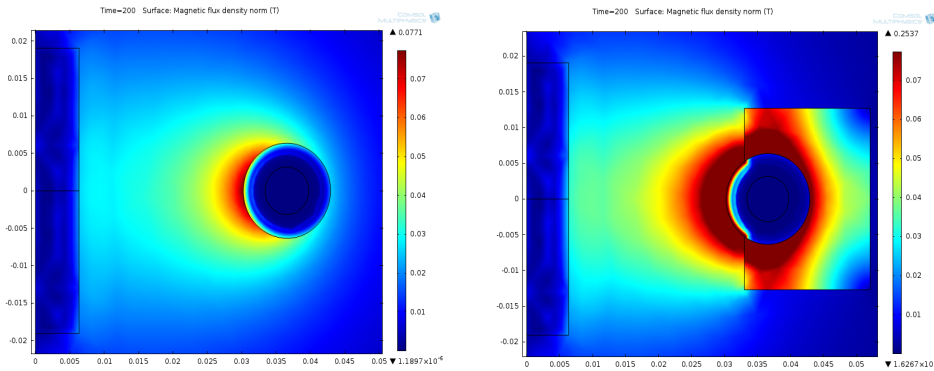


50kW power supply and containment

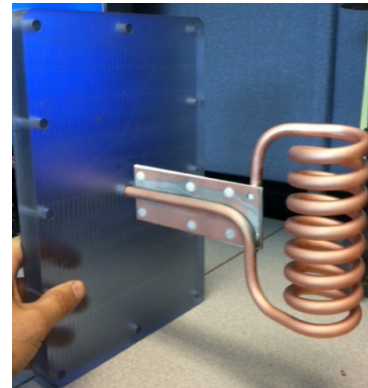


CFEET Coil Optimization

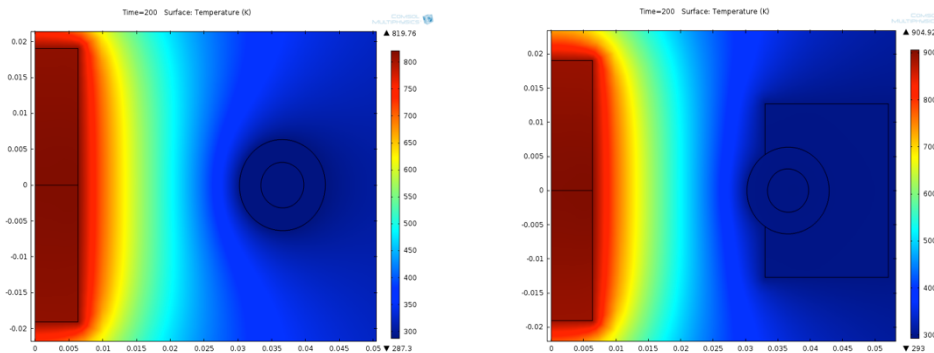
- In-house coil analysis, design and fabrication
 - Evaluated coil diameter, shape, # of turns
 - Evaluated flux concentrator need, materials and submersion of coil



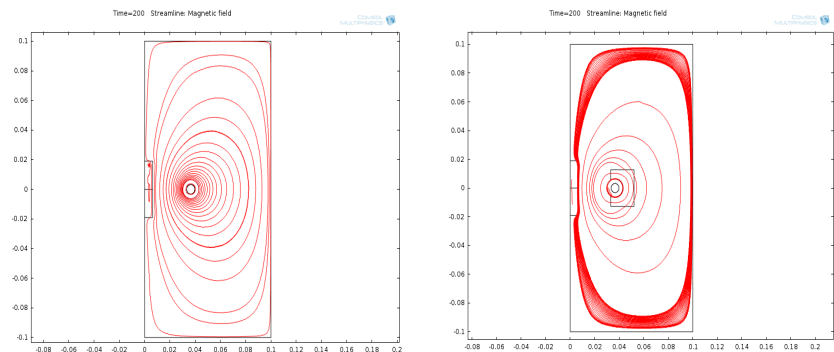
Magnetic flux density without the concentrator (left) and with the concentrator (right)



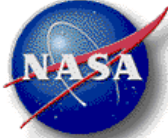
CFEET coil (left) and installed into the chamber (right)



Model of one turn of the coil at 20kW power. Sample energy increased 11% with concentrator (right)



These images show the effect of concentrator on the flux density. With the concentrator the magnetic lines are forced out and coalesce more effectively on the sample (right)



Conclusions

- AES project offers a unique opportunity to develop critical NCPS capabilities and technologies
 - Highly integrated NASA/DOE fuels development team
 - Maximizing use of existing NASA/DOE facilities and infrastructure
- Critical need for materials and process development
 - UO₂ feedstock
 - CVD W coated UO₂ particles
 - Prototypical element manufacturing
- MSFC demonstrated HIP fabrication and testing of CERMET materials
 - Rapid capability development using “proven” materials and processes
 - Dedicated Laboratory for processing of depleted uranium
- Subscale hot hydrogen testing capability exist to screen W-UO₂ fuels
 - Processes, composition, particles size, claddings, and stabilizers
- Full scale element fabrication and test to validate fuel materials
- Enables future affordable, fuel optimization and down select